Helium: Properties, Historical Data, and the Viability of ^{4}He Concentrations in Coalbed Solids in the Powder River Basin

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Contents

Abstract

The properties of helium make it a valuable resource in many industrial and scientific fields. Market volatility, scarcity, and legislative decisions all affect the future of helium refinement, production, and resources. Recently, studies examined the implications of privatizing the federal helium reserve, which is effectively the global supply of helium. Secondary sources of helium, such as extraction from conventional natural gas and responsible practices likely remain the best possible solution to a potential helium crisis. This study aims to examine the potential for helium extraction from coal as an additional alternative. To accomplish this, I conducted a pilot study that examined the potential helium resources in coals in the Powder River Basin located in Wyoming and Montana. I used recently measured concentrations of helium in the Fort Union Formation, Knobloch Coal, and the Flowers-Goodale Coal by thermal fusion of coal seam solids followed by noble gas mass spectrometry from the Ohio State University Noble Gas Laboratory. Remaining, technically feasible coal resources in the Powder River Basin total 1.15 trillion cubic feet with an average helium-4 (^{4}He) concentration of 16,319.93 μcc/kg, or 16.3 ppm. With this figure applied to the entirety of available resources at the Powder River Basin, total helium potential for the basin is 14.4 million cubic meters of ^{4}He. Based on current prices, this indicated a total net worth of approximately 102 million USD. While this number might initially appear high based on present technologies and prices, this volume does not represent a viable or practical source of helium considering the amount of coal that would need to be harvested to obtain this helium. At best, this field only has the potential to fulfill a regional helium demand or serve as a resource with anticipated increased prices in a global crisis. Under certain circumstances, such as CO_2 sequestration during the burning of coal, small amounts of helium could be harvested from the

emission stream of coal combustion plants and may warrant further consideration with the advent of future technologies.

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List of Figures

List of Tables

1.1 Introduction

Helium is the second most abundant element in the universe with many unusual properties (Bradshaw and Hamacher, 2013). Its low density, inertness (Leachman, 1985), low boiling point, and high thermal conductivity (DOI et al., 1978) make up some of its most useful industrial qualities. The extreme nature of this element's properties makes it an irreplaceable resource in many fields of technology, medical, and military applications (BLM, 2015a).

The future of domestic and global helium production is a current topic of debate. Since helium's discovery as an important resource, the United States federal government has been an important and influential figure in the production, storage, and sale of helium (Spisak, 2013). The Bush Dome in the Cliffside Field near Amarillo, Texas, has acted as a helium storage unit for the federal government since 1960 (Spisak, 2013). In 1996, an outstanding debt of 1.37 billion USD owed to the United States Treasury by the United States Bureau of Mines (now the Bureau of Land Management) for purposes of stockpiling helium in the Cliffside Field, warranted congressional intervention for the federal helium program (Spisak, 2013). In 1996, Helium Privatization Act legislation required the Bureau of Land Management (BLM) to begin selling off the federal helium reserve (U.S. Congress, 1996). This created a market scare due to the reserve's importance in the helium supply chain. In 2013, just a few years before the privatization of the federal helium reserve was set to be completed, congress passed the Helium Stewardship Act in order to ensure a smoother market transition (U.S. Congress, 2013).

The most viable source of helium currently lies in conventional natural gas production (BLM, 2015b). Radioactive decay within the Earth creates helium nuclei, which eventually escape into the atmosphere (Bradshaw and Hamacher, 2013). Geologic traps, which store natural gas, can often accumulate helium overtime as helium migrates preferentially to higher molecular weight natural gas components (Bradshaw and Hamacher, 2013; Darrah et al., 2014; Darrah et al., 2015). The length of this process, similar to natural gas, makes helium stored within the earth a non-renewable resource (BLM, 2015b). The non-renewability of helium, and volatile natural gas market trends fueled by government policy and new production technologies, indicate the importance of studies that examine secondary helium resources.

While the threat of a helium shortage may not occur imminently, estimations using current production rates place helium exhaustion at approximately 50 to 80 years from the time of writing, while the strategic helium reserve contains only approximately five years of helium supply (Mohr and Ward, 2014). Estimations for helium reserves in the United States total 3,491 kilotons (kt), and global reserves total 8275 kt. Estimations for helium production from natural gas peak around the years 2060 to 2075, or 2090 to 2100 respectively, depending on steady or decreased consumption (Mohr and Ward, 2014). With shale gas and unconventional natural gas production threatening conventional natural gas production (USEIA, 2015), the future of helium refinement may additionally be threatened. This complex problem leaves the future of helium production unknown.

While there are no obvious solutions for meeting growing global helium demands, numerous complex solutions have been proposed. Examples include helium nuclei generated in nuclear power plants, atmospheric refinement, and missions to the moon and/or other planets (Bradshaw and Hamacher, 2013; Wittenberg, 1986). While helium exists at a concentration of 5.2 ppm (v/v) in the atmosphere, the volume of atmosphere needed, approximately 100 cubic kilometers per day, dramatically exceeds current industrial refinement capabilities (Bradshaw and Hamacher, 2013). More practical and responsible solutions include general conservation and helium recycling (Clarke et al., 2013).

This study aims to accomplish two tasks. The first is to establish a condensed resource on the history, industrial uses, refinement, production data, anticipated demand, and legislation of helium. The second is to examine the potential for helium extraction from coal and consider if this is an economically viable resource of helium. We accomplish the latter by examining coalbeds in the Powder River Basin located in Wyoming and Montana.

1.2 Background

1.2.1 Properties of Helium

Helium (He) is the second most abundant element in the universe (Bradshaw and Hamacher, 2013). Its properties make it an irreplaceable resource (BLM, 2015a). On the Earth, helium exists as a colorless, tasteless, and odorless gas (DOI et al., 1978). It is non-flammable and chemically inert (BLM, 2015a); in fact, helium is the most chemically inert element in nature (BLM, 2015b). Gaseous helium has an extremely low density (Leachman, 1985), while both gaseous and liquid helium exhibit high thermal conductivities (DOI et al., 1978; Wilks, 1967).

The helium molecule has the smallest atomic radius of any element, and therefore has the weakest van der Waals attractive forces (Wilks, 1967). At 4.21 Kelvin (K), the boiling point of helium-4 (^{4}He) is the lowest of any element (Wilks, 1967). ^{4}He does not have a freezing point at 1 atmospheric pressure (atm), however it will solidify under the pressure of 25 atm, as the temperature approaches 1K, and remains remarkably compressible in its solid state (Glyde, 1994). Both helium-3 (^{3}He) and ^{4}He can form three different crystal structures in their solid form, and remain considerably less dense than their liquid states (Wilks, 1967).

Another unusual property of He is its ability to become superfluid when cooled to temperatures below its boiling point. As the temperature of He approaches 2.17K, the specific heat diverges, which is termed the lambda transition (Wilks, 1967). Other physical anomalies occur when cooled around this temperature. At 2.2K, He obtains a maximum density with a discontinuous slope. Keesom and Wolfke noted this transition in 1928; however, it was first observed in 1911 by Kamerlingh Onnes that once cooled below 2.2K, He expands (Glyde, 1994). These two phases are referred to as Helium I (>2.2 K) and Helium II (<2.2 K) (Glyde, 1994). The viscosity of helium II is considered zero, as it is on the order of 10^6 times smaller than that of helium I. The viscosity is so low that if helium II is contained in a capillary tube under certain conditions, it will flow up and over the edges of the tube (Wilks, 1967). These properties are generally thought to be macroscopic examples of Bose-Einstein condensation, which is the backing theory for the "two fluid model." One part of this theory is that as temperatures approach 0K, He is 100% superfluid, and between 0 and 2.2K, part of the fluid carries the entropy, which allows it to exist partially in a superfluid state and partially in a normal state (Glyde, 1994). While properties of these phases were noted early in the 20th century, it was not until 1938 that the ability of He to become superfluid was discovered independently by Allen, Misener, and Kapitza (Vinen, 2004). It is the high thermal conductivity and low boiling point of He that makes it such a valuable resource in cooling and thus essential for a variety of technical applications.

1.2.2 Helium on Earth

The two most common, and the only stable isotopes of helium are helium-3 (^3He) and helium-4 (^4He), the latter being the most abundant on Earth. A third isotope of helium exists (^6He), although this isotope is exceedingly unstable, with a half-life of only 0.82 seconds (Wilks, 1967). Helium exists in the atmosphere at a concentration of approximately 5.23 ppm (Bradshaw and Hamacher, 2013). The majority of this concentration is composed of ^4He, with ^3He only making up about 1.39 x 10^{-6} of this fraction (Keller, 1969). Helium is concentrated in the Earth's crust in comparison to atmospheric concentrations, groundwater, or the Earth's mantle. The movement of fluid in the Earth's crust, by tectonic, magmatic, or hydrological processes, can further concentrate helium. Because of these processes, helium is typically in geologic traps that collect migrated fluids, as a minor constituent in natural gas (Darrah et al., 2014; Darrah et al, 2015). The United States Geological Survey (USGS) estimates that approximately 8 million tons of helium resides in the Earth's crust (Clarke et al., 2013). While trace amounts of helium exist in virtually all natural gas, it has been found at concentrations as high as 8% in certain fields (Leachman, 1985).

Approximately 95% of the Earth's helium results from nuclear alpha decay within the Earth's crust; the remaining 5% could be of stellar or primordial origin. Both isotopes of ^{3}He and ^{4}He were produced just moments after the big bang (Izotov and Thuan, 1998), and it is thought that the abundance of ^{3}He on Earth is left over from these early nuclear reactions. Within the Earth's crust, ^{4}He is emitted as alpha particles during the nuclear decay of Uranium (^{238}U) and Thorium (^{232}Th) (Bradshaw and Hamacher, 2013). This has produced trillions of cubic feet of ^{4}He since the formation of the Earth (Spencer, 1983), however only a small fraction of this helium remains on our planet.

A discontinuity occurs when examining the helium production potential from ^{238}U and ^{232}Th since the formation of the Earth, compared to the corresponding levels of helium still present on the Earth, specifically in the Earth's atmosphere (Bradshaw and Hamacher, 2013). The rate of formation of ^{4}He and the rate of degassing from the Earth's crust into the atmosphere are nearly equivalent at approximately 3×10^{3} tons per year (Bradshaw and Hamacher, 2013). Estimates suggest that ~1×10^{14} tons of helium have degassed into the atmosphere since the formation of the Earth (Bradshaw and Hamacher, 2013). With an atmospheric concentration of only 5.23 ppm, this implies that a mass of ^{4}He of nearly 1×10^{14} tons has already escaped from the atmosphere to space (Bradshaw and Hamacher, 2013). If helium was unable to escape the atmosphere, its concentration would be upwards of 10% (Clarke et al., 2013), or nearly 20,000 times greater than it is today.

Helium's properties of inertness and low density contribute to its ability to escape into space without the need to achieve escape velocity. This process was originally coined "polar wind," although is now a well-studied phenomenon called "ion outflow" (Bradshaw and Hamacher, 2013). Hypotheses of ion outflow mechanisms developed alongside what was originally theorized as a "helium mantle," more specifically an extremely low-density atmosphere of helium existing some 500 km to 5000 km in radius, enveloping the Earth. (Keller, 1969). Today, this layer past the upper atmosphere is known as the ionosphere. The ionosphere consists of O^+, H^+, and He^+ ions existing as a plasma that is virtually free of atomic collision. Although helium in the ionosphere is theoretically not lost from the atmosphere, certain conditions at the Earth's poles create the inevitability of ionized helium flow into interplanetary space (Bradshaw and Hamacher, 2013).

The sun also releases large quantities of helium. In the sun, hydrogen nuclei undergo fusion reactions to produce helium nuclei, which is what gives the sun most of its energy (Spencer, 1983). The production of helium by the sun has led some workers to suggest that the Earth's moon, comets, asteroids, or other planets may be a viable source of helium for human consumption (Wittenberg, 1986).

1.2.3 Helium Applications

The use of helium spans a diverse array of industries and purposes. Perhaps the most profound catalyst of helium as an industry was World War I, and subsequently the demand for new, more efficient technologies in World War II. While helium is still a necessary element for government and military applications, its multitude of unusual properties make it indispensable in many different fields, as shown in Figure 1.

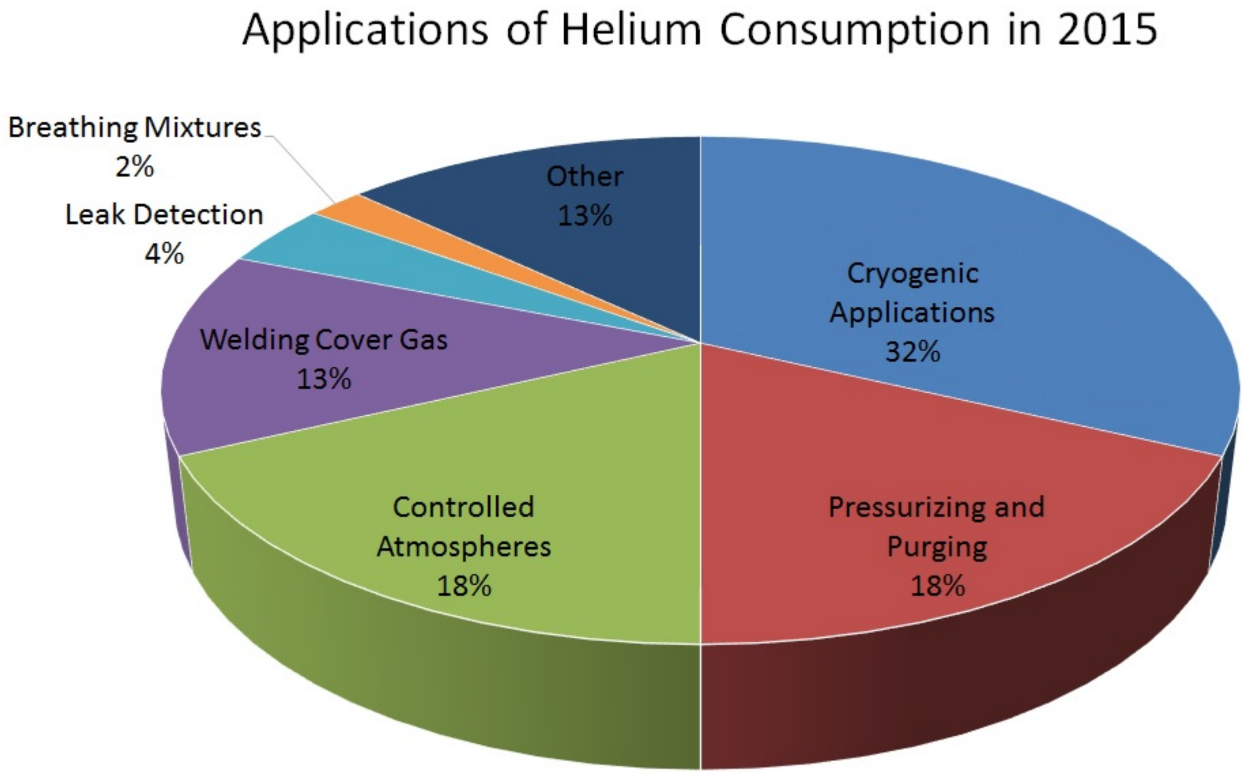

Figure 1. Applications of Helium Consumption in 2015. Statistics courtesy of USGS Minerals Commodity Summary (Hamak, 2016).

For many of these applications, helium is the only choice. Its low boiling temperature is not rivaled by any element, which is why it is necessary for many cooling applications. The sizable electromagnets used in magnetic resonance imaging (MRI) machines depend on liquid helium cooling. Other cooling applications include physics research, nuclear reactor cooling, and thermographic cameras (BLM, 2015a).

Since helium is the most inert element, it is an irreplaceable choice for use as a controlled atmosphere in a variety of applications, including the semiconductor industry. Silicon wafers are grown in inert (e.g., helium) atmospheres to insure the highest level of quality possible (BLM, 2015b). Its inertness is also necessary for use as a welding cover gas, similar to a controlled atmosphere (BLM, 2015a). Helium is also vitally important to space exploration. NASA and other agencies use helium to keep gases and liquid fuel separated during rocket lift offs (BLM, 2015b).

Helium can act as a replacement for nitrogen in certain breathing mixtures, especially those used for divers (i.e., tri-gas breathing mixtures) (Spencer, 1983). When surfacing, decompression can cause a phenomenon known as “the bends,” in which tiny nitrogen gas bubbles form at fatal concentrations in the diver’s blood (Spencer, 1983). Since helium has an extremely low solubility, it is a safe replacement for nitrogen in this artificial breathing gas (Spencer, 1983).

Leak detection is done most efficiently with helium due to its low density (BLM, 2015a). Special helium detection equipment can detect infinitesimally small quantities, to the extent where thousands of years would be required for any measureable volume to pass through an opening (Spencer, 1983). This is useful for manufactures when testing the quality of appliances and products such as tires, fire extinguishers, refrigerators, aerosol, and air conditioners (BLM, 2015b).

The “other” category even takes into account party balloons. Even though helium is a rare and indispensable element, its use for wasteful applications persists. When a helium filled party balloon rises into the atmosphere, the helium contained within it will eventually, and indefinitely, reach interplanetary space (Bradshaw and Hamacher, 2013). Some industry critics believe the cost of helium needs to be set artificially high in order to keep this precious resource from being squandered.

1.2.4 History of Helium in the United States

The history of helium as an industry extends back to the early 20th century. It was first discovered during a solar eclipse on August 18th, 1868 (Pacheco, 2002). British and French astronomers Norman Lockyer and Pierre Janssen discovered helium simultaneously. Helium presented itself to these men as an unknown yellow spectral line during the night of this eclipse, and was later named helium after “helios,” the Greek word for “sun.” (Spencer, 1983). It was not until nearly 40 years later in 1905 that Dr. H. P. Cady discovered helium in low quantities in some natural gases. The properties of helium became a topic of importance to countries such as Germany, the United States, and Great Britain. Helium was not yet widely available for use in World War I; however, the Bureau of Mines recognized its potential as a powerful lifting gas and started funding helium research as early as 1917 (Spencer, 1983). Second in density only to hydrogen, helium was recognized as a far safer lifting gas due to its inertness versus the highly flammable nature of hydrogen (Seibel, 1968).

According to the USGS 2000 Minerals Yearbook for Helium (Pacheco, 2002), the first helium refinement plant started operation after World War I, in 1921. This plant was built near Fort Worth, Texas and refined natural gas extracted from the Petrolia field (Pacheco, 2002). With increased demand, another plant was built near Amarillo, Texas in order to move the operations closer to the sole consumer: The United States Navy. This second plant refined natural gas extracted from the Cliffside Field, which later became and is still to this day, the United States Government’s lone, and the world’s largest, helium storage reservoir. See Figure 2 below for location details of this field and other United States helium reserves.

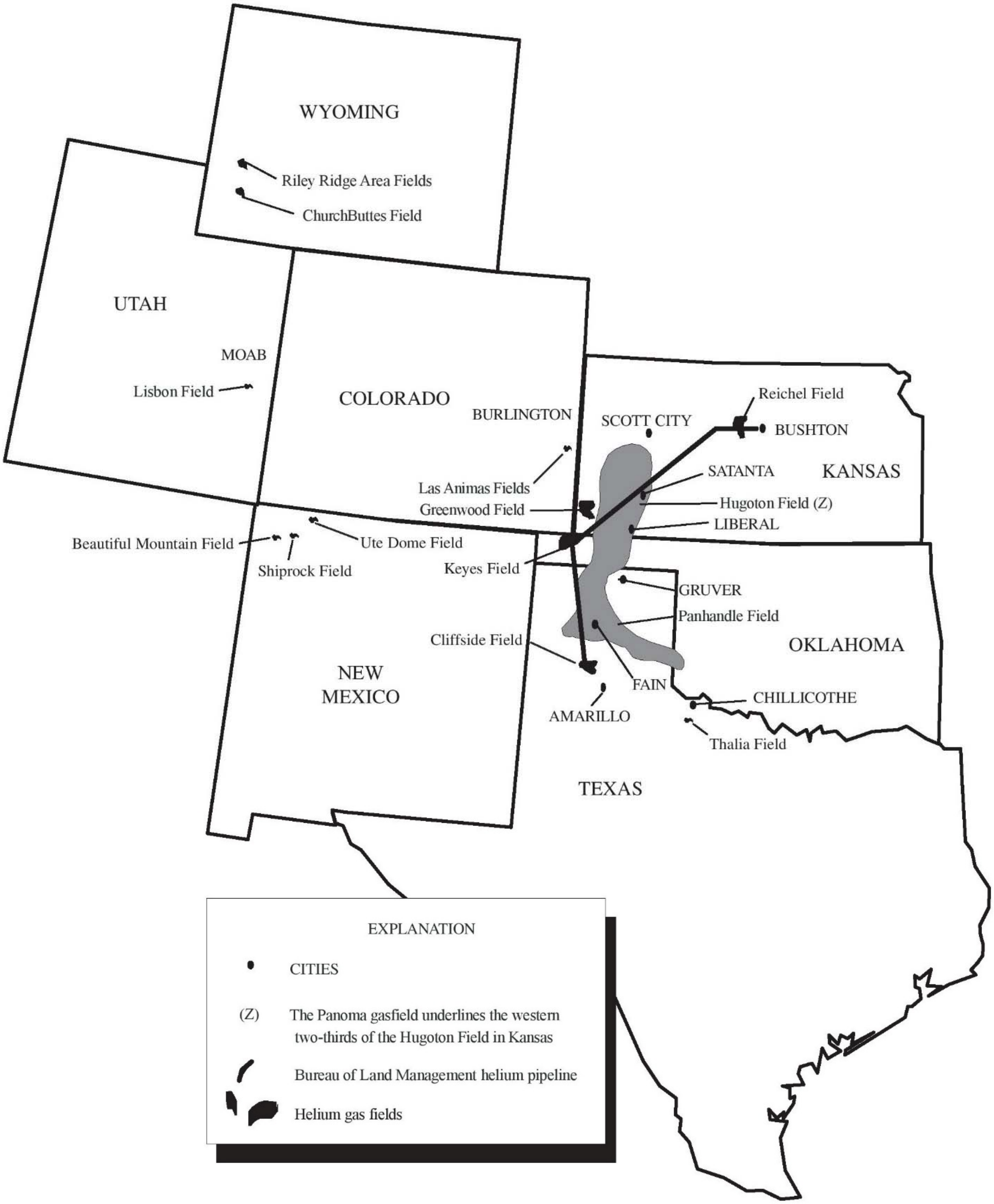

Figure 2. Major US Helium-Bearing Natural Gas Fields. Image courtesy of USGS Minerals Yearbook, (Pacheco, 2002).

As uses and demand increased, the government realized that the supply of helium was potentially extremely volatile. Only certain wells contained economically viable amounts of helium, and of those, much was lost to the atmosphere through venting, (a process in which natural gas is allowed to escape freely from a well in order to depressurize it), or because it is not economically viable. In 1983, estimates suggest that around only 7% of the helium content contained in produced natural gas was refined that year, and the rest vented to the atmosphere (Spencer, 1983).

In the United States, there have been four major laws, and their associated amendments, passed regarding the refinement, and storage of helium. Once recognized by the government as a valuable "mineral" resource, congress passed the Helium Act of 1925, which authorized the Secretary of the Interior to take land through the means of purchase, lease, or condemnation, where helium could be refined for use by the U.S. Army and Navy (U.S. Congress, 1925). Shortly after the U.S. government purchased the Cliffside Field, the aforementioned Amarillo plant supplied demand almost solely for the U.S. Navy during World War II. Congress allowed the expansion of this plant in 1941, which increased the production of helium to nearly 3 million cubic feet (Mcf) per month (Seibel, 1968); however, this would still not meet military demands, which were fueled almost entirely by the airship program. President Franklin D. Roosevelt approved over 200 "lighter-than-air ships," and approximately 17 million dollars was set aside for the construction of new helium refinement facilities (Seibel, 1968). By the mid-1940s, the annual helium demand had grown to 400 Mcf (Seibel, 1968).

After Japan's surrender in 1945, the airships used during the wartimes were slowly decommissioned and the demand for helium greatly reduced. At this time, no other application for helium could produce a demand that rivaled that of the U.S. Navy, so talk of dismantling the existing plants was entertained. While many wanted to salvage the resources used in these plants, the U.S. Department of the Interior decided to keep them on stand-by for potential future needs.

Coincidentally, another application for helium related to the dismantling of wartime equipment arose that further increased demand. By the early 1950s, many helium plants were up and running again (Seibel, 1968). Arc welding was used for the recovery of rejected magnesium aircraft parts, and helium was the inert cover gas of choice for use in this process. This even created demand for higher purity helium, and therefore better refining processes. Wartime helium had a purity of ~98.2%, which has since been replaced with what is known today as Grade-A or "two nines" helium, approximately 99.995% purity (Seibel, 1968). Grade-A helium quickly became the industry standard and has represented 100% of the volume of helium purchased by the federal government since 1950 (Seibel, 1968).

At this point, it became clear that helium was an invaluable resource, and if not conserved, exhaustion was imminent. The 2 million cubic feet (2McF) held in the Cliffside Field was estimated to last through the end of the last century (Seibel, 1968). Although the Mineral Leasing Act of 1920 guaranteed the federal government rights to all helium produced on leased federal land, private refinement of natural gas held no interest in helium so it was often wasted during the refinement process. With this knowledge, the government decided to create a market value, in the form of a new law. On September 13th 1960, the second major helium act was passed, known as the Helium Act Amendments of 1960 (Seibel, 1968). This act allowed the Secretary of the Interior to create contracts with private parties in order to refine and conserve helium, and also to purchase or seize land if no reasonable contract could be made (U.S. Congress, 1960). This program was overseen by the Bureau of Mines, and set in motion for a period of 25 years (Spisak, 2013). Contracts for this program became active in 1962; the act resulted in the construction of five new refinement plants, and the purchase of approximately 50 million dollars of helium per year, for 22 years (Seibel, 1968). While up until this point global production remained largely inactive, the United States' foresight in this precious resource sparked a barrage of new helium applications and demands (Figure 3).

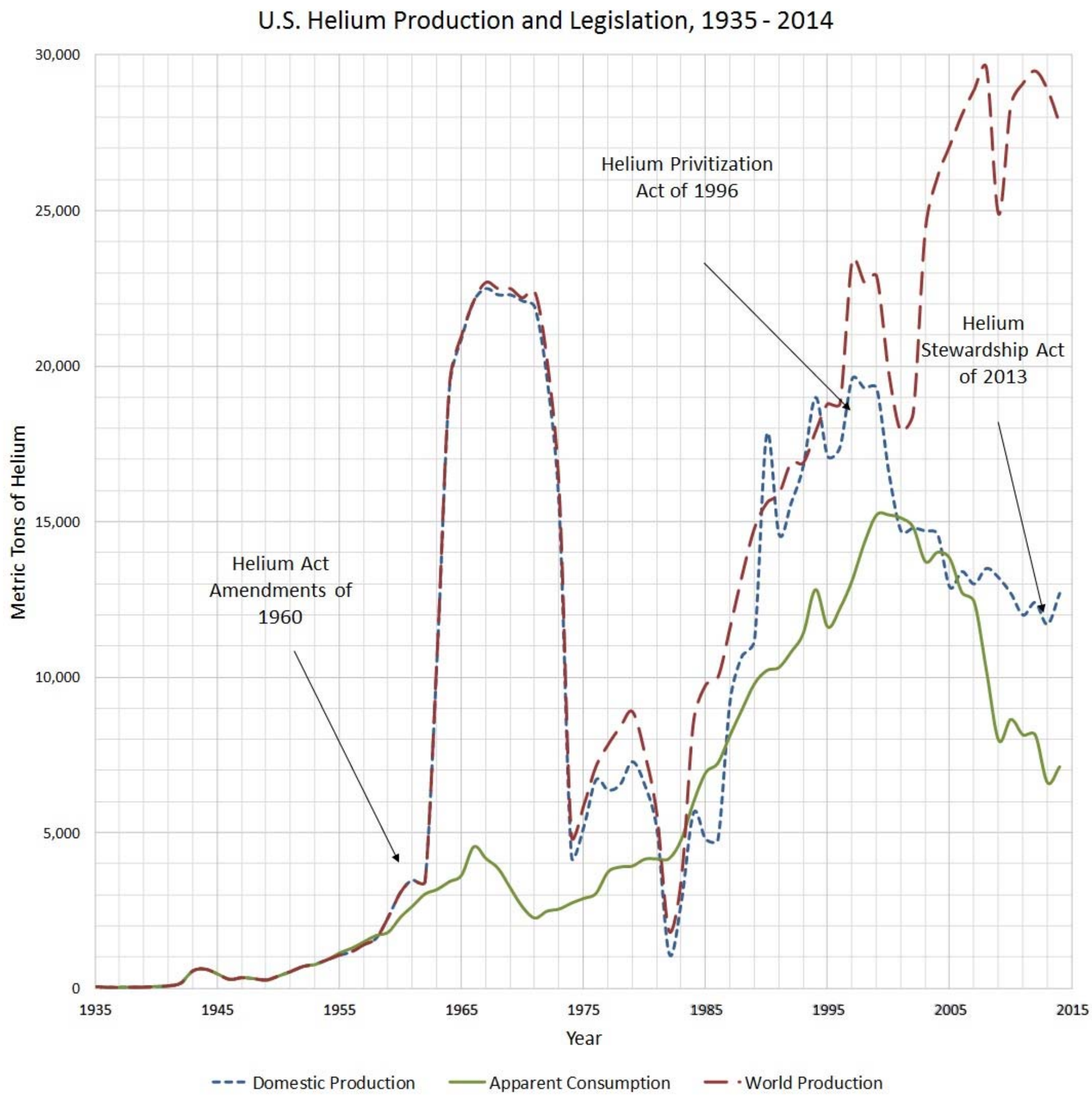

Figure 3. U.S. Helium Production and Legislation, 1935 – 2014. Statistics courtesy of USGS Historical Statistics for Mineral and Material Commodities in the United States: Helium Statistics, (Kelly et al., 2016).

A sharp spike in helium production is observable, starting in the year 1962. Funding for the acquisition of private helium came in the form of a loan from the U.S. Treasury (Spisak, 2013). Total cost of helium for the Bureau of Mines under the Helium Act of 1960 was 252 million USD (Spisak, 2013). This sum was originally set to be repaid by 1985, 25 years after the inception of the program. However when this time arrived, none of the loan had been repaid and the interest plus principal had grown to 1.3 billion USD (Spisak, 2013). Congress froze this debt at 1.37 billion USD with a ten-year extension, although by 1995 the Bureau of Mines had still made no progress toward repaying the U.S. Treasury (Spisak, 2013).

While this act served its ultimate purpose of conservation, it accomplished this purpose at the cost of economic success. In 1995, the debt of 1.37 billion USD remained outstanding, calling for more government intervention. Consequently, the Helium Privatization Act (HPA) of 1996 was signed into law, which allowed the Secretary of the Interior to "enter agreements with private parties for the disposal of federal helium" (U.S. Congress, 1996). This law was virtually an exact reversal of the Helium Act Amendments Act of 1960, in that it required the Bureau of Mines to sell off its 30.5 billion standard cubic feet (scf), leaving only 600 million scf, in the Bush Dome Cliffside Field for "permanent reserve" (Spisak, 2013). Had this act been fully carried out, only 2% of the original stockpile would have remained. The HPA required the sell off to begin in 2005 in order avoid market manipulation; however, a steep decline in domestic helium production is seen in Figure 3, starting in the year 1999. Since 1995, nearly all of the debt owed to the U.S. Treasury has been paid, leaving only 44 million USD outstanding in 2013 (Spisak, 2013). With virtually no helium stockpile remaining, the threat of a global helium shortage arose.

With the debt nearly repaid, the Helium Privatization Act of 1996 had fulfilled its purpose, although it remained in place at the expense of the U.S. Strategic helium reserve and the stability of the global helium supply. Under this law, the BLM was still required to continue the privatization of what remained of the helium supply. In July of 2013, a speaker on behalf of the U.S. Department of the Interior delivered a statement before congress which addressed the issue of the dwindling state of the federal helium reserve. The HPA would require virtually all of the remaining volume to be sold by 2015 (Spisak, 2013).

To address the issue of a possible global helium shortage, congress passed the Helium Stewardship Act (HSA) of 2013, which amended the HPA, and remains in place today. The HSA seeks to continue the sale of helium by the federal government, while continuing refinement operations and maintaining a fair market value. This is intended to stabilize both the market and supply, with the ultimate goal of a smoother transition to privatization (U.S. Congress, 2013).

The HSA laid out four phases of action to accomplish the task of helium privatization successfully. The first was to continue as usual under the HPA until the HSA became active in September of 2014. By this time, all of the U.S. demand for helium and helium exports were fully supplied by private industry. Next, the HSA required the BLM to start auctioning off small volumes of the reserve on an annual basis to qualified buyers, with the remainder sold to refineries with pipeline access (Hamak, 2016). As of 2016, under terms of the HSA, the BLM has brought in tens of millions of dollars in revenue from their annual helium auction (BLM, 2016). Phase three of the HSA is projected to begin in October of 2018, after the total volume of helium remaining in the reserve reaches 3 billion cubic feet. During this phase, private sales and auctions cease, but federal use of the reserve continues. In the fourth phase, the Secretary of the Interior is required to start disposing of assets relating to the United States ownership and rights to underground natural resources. It also requires certain government agencies, such as the United States Geological Survey (USGS), Department of Energy (DOE), and BLM to create assessments of helium resources, supply, and demand; select assessments are estimated to be finished by 2018. This phase is not set to be implemented until September of 2021, insuring a smooth market transition as helium is eventually completely privatized (Hamak, 2016).

1.2.5 Global Helium Production and Resources

As seen in Figure 3, the United States was the only influential producer of helium until after 1975. By 2000, the United States still dominated the market and was responsible for 80% of the world's helium production (Pacheco, 2002). In 2014 (the latest information available from USGS), the United States produced only 46% of the global helium supply. This is due to both a decrease in overall U.S. production, and an increase in production from other countries. (See Figure 3 for domestic production vs. world production). U.S. exports of helium have also dramatically increased, implying a higher demand in other countries, while the U.S. demand diminishes due to new, more efficient technologies. Around 2013 to 2014, we see a sharp reversal in exports and consumption. This can be attributed to the both the HSA, and increasing international production (Figure 4).

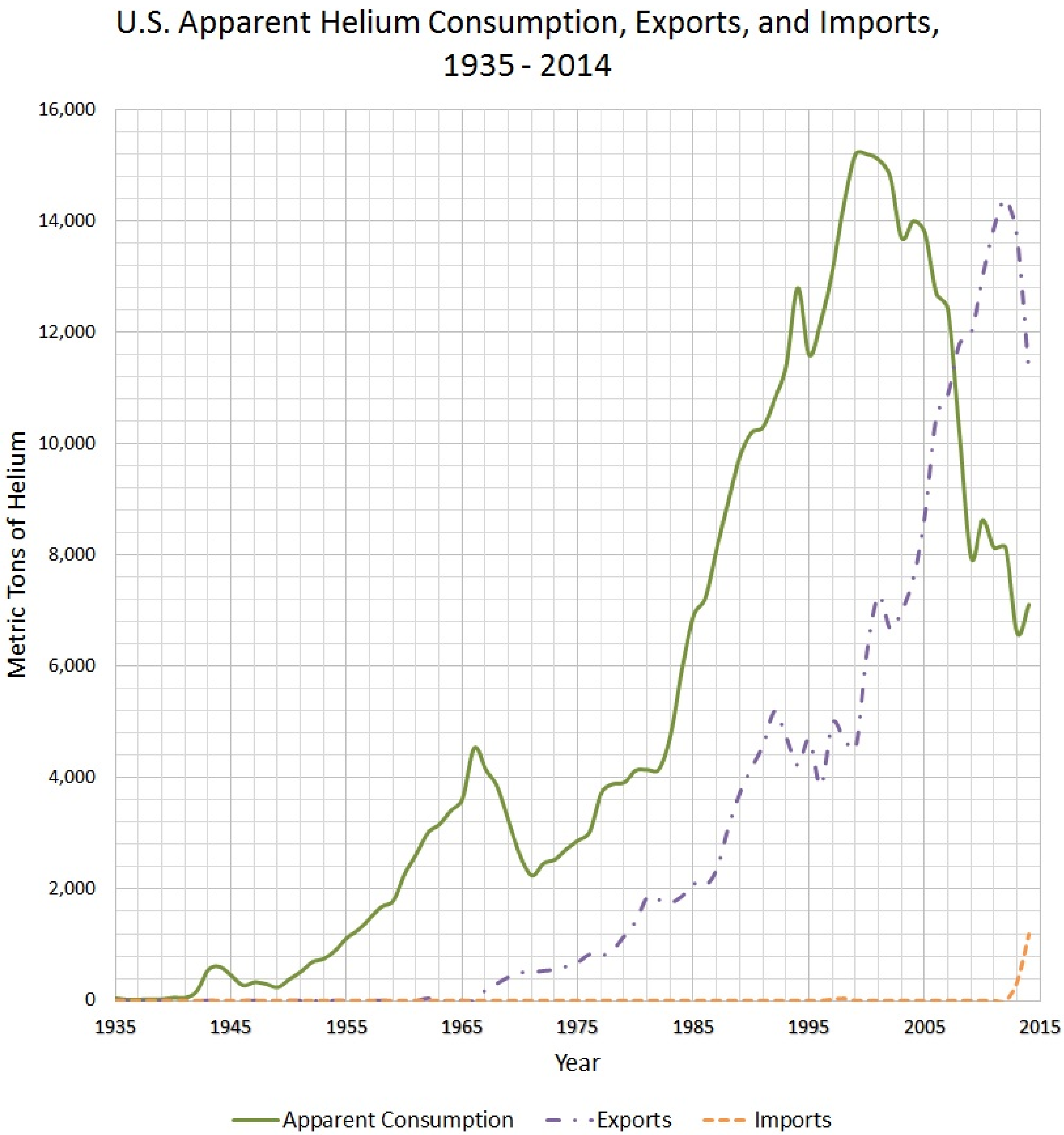

Figure 4. U.S. Apparent Helium Consumption, Exports, and Imports, 1935 – 2014. Statistics courtesy of USGS Historical Statistics for Mineral and Material Commodities in the United States: Helium Statistics, (Kelly et al., 2016).

While the United States has remained the most powerful producer of helium in history, viable helium reserves span only 11 states and include only 102 proven natural gas fields. Still, the majority of production comes from only six fields. These fields include the Cliffside Field in Texas, the Riley Ridge area in Wyoming, the Hugoton Field, which spans Texas, Oklahoma, and Kansas, the Keyes Field in Oklahoma, and the Panoma Field in Kansas. A major BLM pipeline connects a portion of these fields to the Cliffside Federal Helium Reserve near Amarillo, Texas (Hamak, 2014) (See Figure 2). In 2014, five other countries were major producers of helium. These countries include Algeria, Australia, Poland, Russia, and Qatar (Hamak, 2014). Of these countries, Algeria is the top producer, although Qatar is estimated to have the most helium reserves besides the United States (Table 1). For further information and reading on helium reserves of the world, the publication cited for Table 1 holds a very complete and in depth look at this topic.

Table 1. Helium Production and Resources of the World by Country. Statistics courtesy of "Helium Production and Possible Projection," in Minerals, (Mohr and Ward, 2014).

Country	Cumulative Prodution (kt He)	Resources (kt He)	Ultimately Recoverable Resources (kt He)
USA	687	3491	4178
Qatar	14	1710	1723
Algeria	47	1388	1435
Russia	26	1151	1177
Canada	2	339	340
China	0	186	186
Poland	10	5	15
Australia	3	5	8
World	**789**	**8275**	**9064**

1.3 Helium Problems

Since the enactment of the HSA, the imminent threat of a global helium shortage has subsided, although whether an indefinite supply for the future is insured is still debated. Even the most generous estimations do not foresee our current methods of helium production remaining viable for the remainder of the century. An in-depth analysis of the world helium reserves and supply was published in the midst of panic in *Minerals–Open Access Mining & Processing Journal* in 2014. The authors predicted that helium production will likely not plateau until 2060–2075, or until 2090–2100 depending on production models (Mohr and Ward, 2014). Others suggest that helium supply would not be at risk due to market bottleneck trends, the inevitability of helium imports, and the ever-increasing efficiency of industrial uses of helium (Clarke et al., 2013). However, in 2011, the same publication listed helium as a "serious threat in the next 100 years," and their estimated outlook still does not see helium lasting through the next century (Pitts, 2011). While industrial use of helium is getting more efficient, current market value often makes buying new Grade-A helium, and disposal of used helium, more economic than recycling (Clarke et al., 2013).

Currently our only viable source of helium is helium-rich natural gas. While all natural gases contain at least trace amounts of helium, very few fields contain high enough concentrations to be worth refining. Additionally, the economic viability of helium in some natural gases usually comes as a secondary component to the primary economic viability of the carbon content of the gas, (an industry that is approximately one thousand times larger) (Clarke et al., 2013). This means that if helium is the primary value in natural gas, it still may not be economically viable to produce. The market price of helium may also render the secondary value of helium more of a burden to exploitation companies than is worth the effort of refinement. This is what government intervention elected to stop with the Helium Act Amendments of 1960, although at a multi-decade economic loss. With these factors in mind, the options for refining helium in the free market remain somewhat limited. Even with laws in place and modern refinement technologies, upward of 50% of today's helium is either vented, or lost during natural gas refinement (Clarke et al., 2013). Artificially high prices would be an easy solution to this problem, but only at the cost of the consumer, and the necessity for broad government outreach on a global scale.

The major problem with helium that seems to go unaddressed is its non-renewability in the span of human life, and unlike other non-renewable resources, no other element can be substituted for many of its uses. Currently, the only way helium is generated is through radioactive decay, which as previously addressed, cannot be an effective natural source on a human time scale. Other sources of natural gas have been explored, and while certain nitrogen fields have been proven to contain viable concentrations of helium, shale gas only contains trace amounts and does not appear to be a viable source (Clarke et al., 2013; Bradshaw and Hamacher, 2013).

This advent of shale gas production may present a new problem. Shale gas in the United States has the potential to replace many other forms of natural resources; this relatively new branch of the petroleum industry could halt natural gas production from conventional reservoirs, including those containing the United States' only viable helium supply (USEIA, 2015). This could make the United States, and subsequently future technologies we develop, completely reliant on foreign sources of helium.

1.4 Backstop Solutions to a Potential Helium Crisis

At the time of writing, there has been very little research done in exploring the potential for new sources of helium. While there is currently no other viable source besides helium-rich natural gas, other potentially viable sources do exist. Most publications remain extremely pessimistic about sources besides natural gas, and research yields very little progress in working toward a renewable, or even last-ditch effort resource. This opens up an opportunity to propose solutions and prepare for what looks like an imminent helium shortage, no matter how optimistic the immediate future looks.

The most obvious backstop source of helium is the atmosphere. While atmospheric helium concentrations exist at only 5.23 ppm, the atmosphere would offer a nearly renewable solution for the helium problem. However, issues with this solution arise with the volume of atmosphere needed to keep up with global helium demand. In 2013, it was estimated that approximately 100 cubic kilometers of atmospheric gas would need to be refined on a daily basis in order to match global demand (Bradshaw and Hamacher, 2013). This presents various issues, such as the cost and energy demands to carry out such refinement, and engineering challenges. In 1983, estimations put the cost of atmospheric helium production at approximately two orders of magnitude beyond the cost of helium derived from natural gas (Spencer, 1983).

Another solution would be ionosphere refinement, where we know He^+ ions are abundant. Exploration for this idea dates back to the early 20th century, when much less was known about ^3He, and hypotheses suggested that this isotope exists more abundantly, as high as 0.4%, in the upper atmosphere (Keller, 1969). This also presents problems, since the ionosphere is incredibly low density, exists as a plasma, and is hundreds of kilometers from the Earth. For both of these solutions, the theoretical potential is easy to see. The execution of these methods remains a problem of engineering, energy loss, and cost of refinement.

One area of study that has produced promising numbers, although with little proposition as a solution, is coalbed methane (CBM), and coalbed solids. Recently, CBM analysis on coal fields such as the Powder River Basin in Wyoming and Montana, and the Illinois Basin in Illinois, Indiana, and Kentucky, has yielded abnormally high ^{4}He content (Moore, 2016). While refinement of helium from coal would still present issues, this study shows that the potential for viable helium production exists. The remainder of these data presented focuses on the Powder River Basin, specifically the Knobloch and the Flowers-Goodale coal beds in the Montana extent of this geologic formation.

2.1 Geologic Setting of Study Area

The Powder River Basin (PRB) is the largest producing low-sulfur sub-bituminous coal region in the world (USGS, 2013). In 2011, the PRB was responsible for 42% of domestic coal production, totaling approximately 462 million short tons (MST). An estimated 92% of this production came from the Gillette coalfield portion of the PRB in Montana (USGS, 2013). This asymmetric syncline spans across a broad portion of two U.S. states and encompasses 19,500 square miles (USGS, 2013). The coal reserves of the basin are strewn across the entire region, making up many different coalfields which represent a variety of geologic units.

As mentioned in the previous section, this study focuses specifically on data from the Knobloch, and Flowers-Goodale coal seams, and the development of an economic model that applies these data to the basin as a whole. These beds are located in the Tongue River Member of the Fort Union Formation. The mined coalbeds in this formation are located in the southern Montana portion of the PRB and are Paleocene in age (Luppens et al., 2015). The Laramide

Orogeny is responsible for the structural formation of this basin; however, depositional environments that make the area coal rich were due to subsidence of the basin, and uplift of surrounding areas. See Figure 5 below for an idea of tectonic setting. It should be noted that at the time of writing, recent government data still recognizes “Tertiary” as the geologic period for the deposition of the Fort Union Formation.

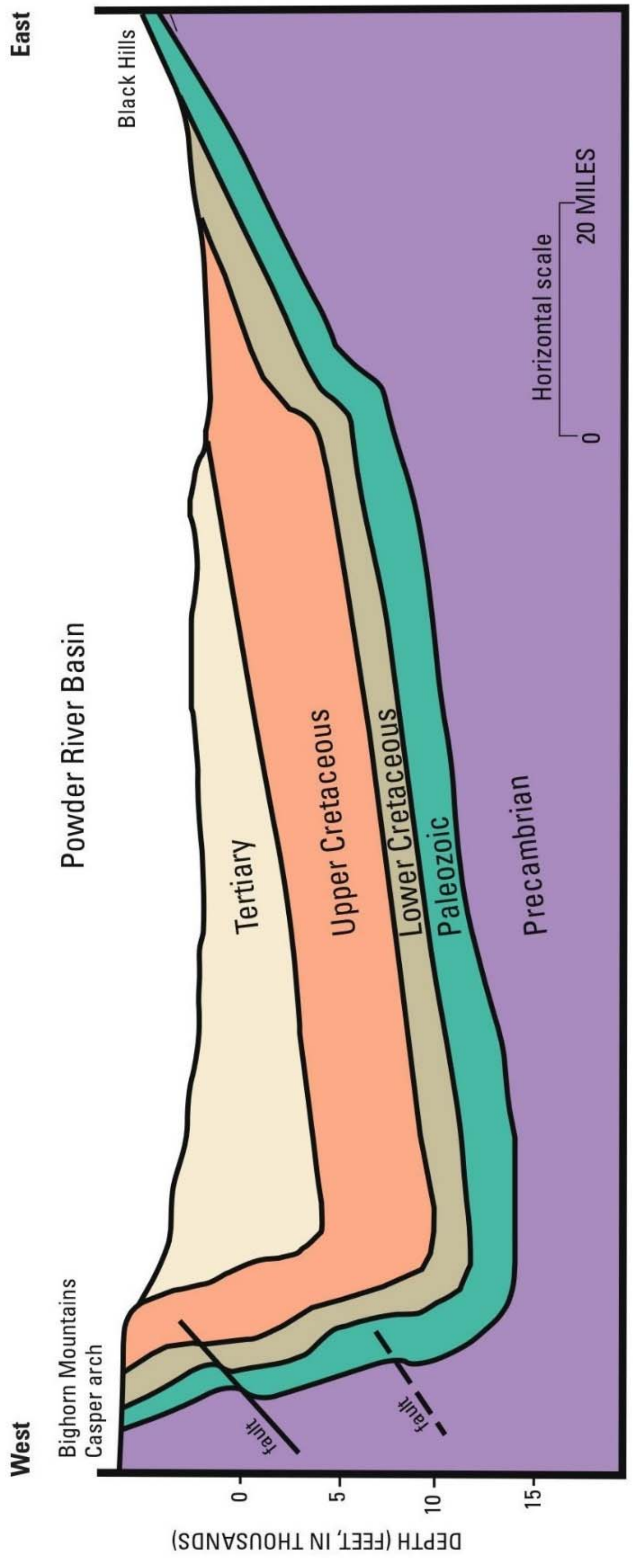

Figure 5. Structure of the Powder River Basin in General East to West Cross Section. Image courtesy of USGS "Geologic Assessment of Undiscovered Oil and Gas in the Powder River Basin Province, Wyoming and Montana," (Anna, 2010).

Sediment of the Fort Union Formation is composed primarily of Cretaceous sediments and some Jurassic to Paleozoic sediments. Depositional environments for the PRB are similar to traditional Pennsylvanian coal swamps, with the exception of accompanied orogenic events. Extensive floodplains and swamps created ideal coal forming environments; fossil evidence suggests a tropical to subtropical paleoclimate, with heavy annual rainfall and moderate annual temperatures. Some coal beds in the PRB are up to one hundred meters thick. This anomaly remains a debated area of study for the region, although it is generally accepted that dramatic tectonic activity paired with erosional and drainage events, contributed to varying lateral thickness of certain units and unusually thick coal beds (Flores and Bader, 1999).

The Fort Union Formation has three members that extend laterally across the basin throughout both Wyoming and Montana; they are the Tongue River Member, the Lebo Shale Member, and the Tullock Member. Viable coal seams exist only in the Tongue River Member of the Fort Union Formation. See Figures 6 and 7 for an overview of stratigraphic information and geographic location for this unit within the PRB. For further information and reading on depositional environments and geological setting see “Coal Geology and Assessment of Coal Resources and Reserves in the Powder River Basin, Wyoming and Montana,” Professional Paper 1809, published by USGS (Luppens et al., 2015).

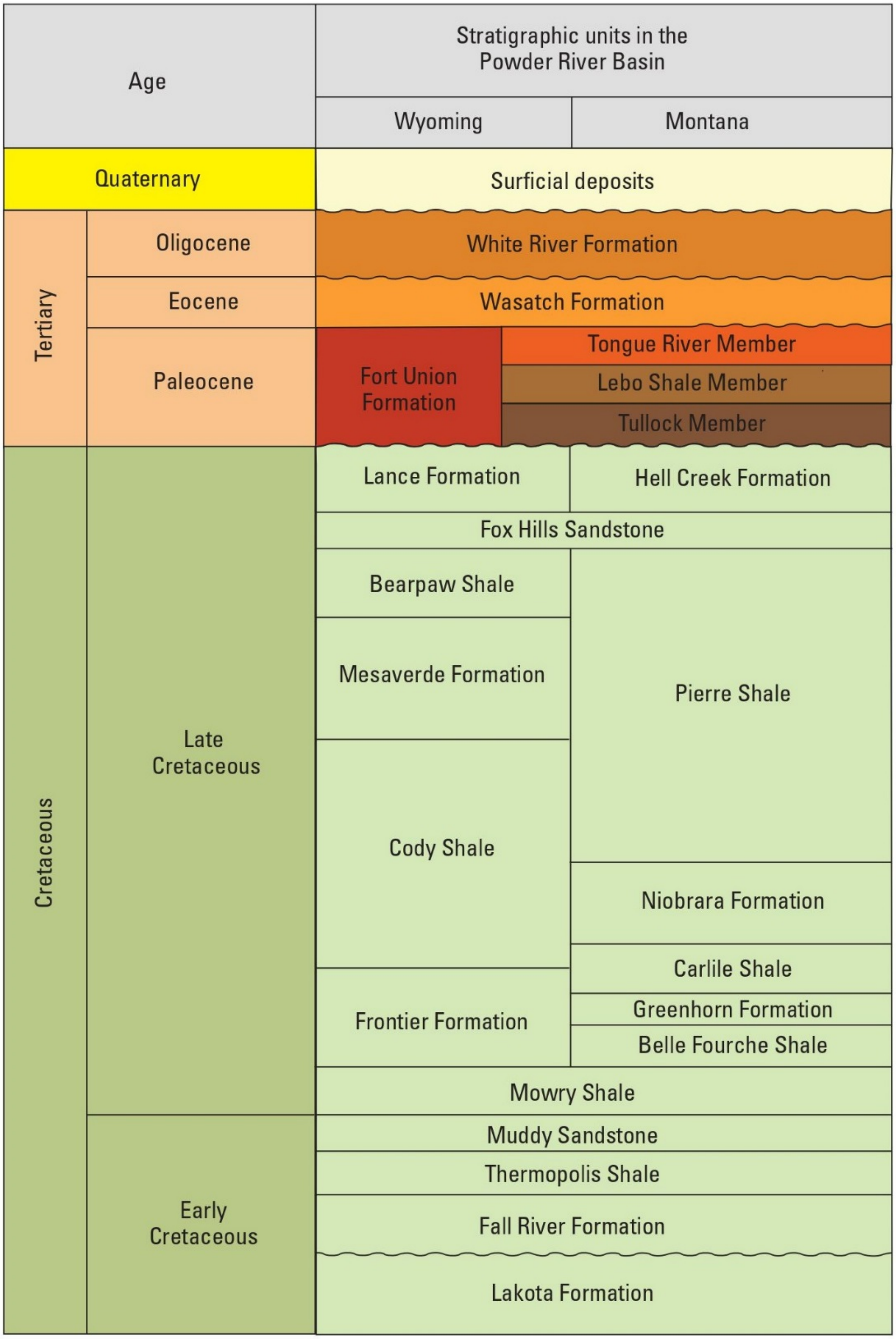

Figure 6. Stratigraphic Column of the Cretaceous to Quaternary in the Powder River Basin. Image courtesy of USGS "Coal Geology and Assessment of Coal Resources and Reserves in the Powder River Basin, Wyoming and Montana," (Luppens et al., 2015).

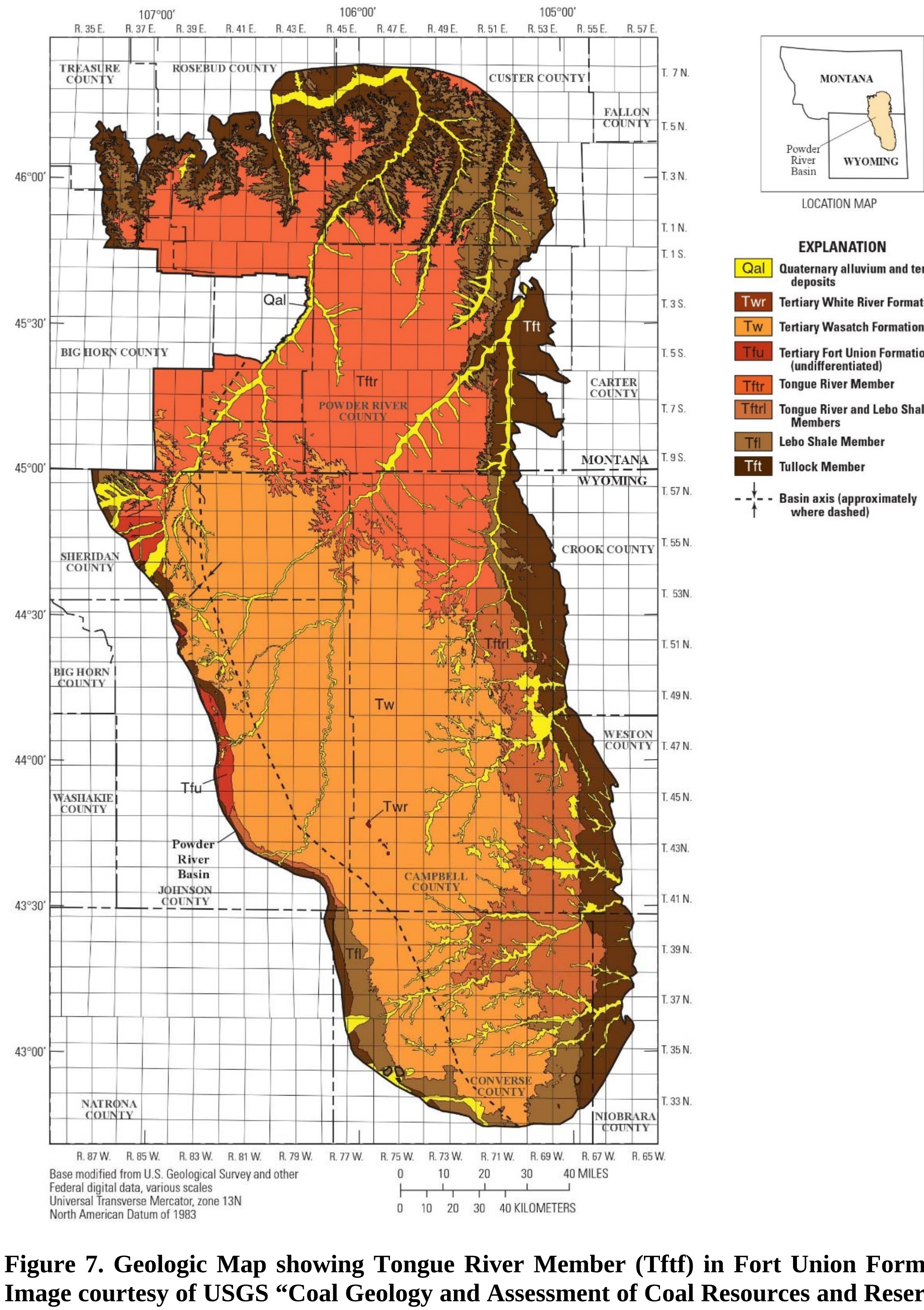

Figure 7. Geologic Map showing Tongue River Member (Tftf) in Fort Union Formation. Image courtesy of USGS "Coal Geology and Assessment of Coal Resources and Reserves in the Powder River Basin, Wyoming and Montana," (Luppens et al., 2015).

2.2 Methods

2.2.1 Methodology for Collection of Data

These data presented herein represent information collected from a number of coal beds in the Powder River Basin. The coal bed samples analyzed for use in this study are courtesy of Maverick Energy and were analyzed by Dr. Thomas Darrah at the Ohio State University Noble Gas Laboratory. Solid coal seam samples were collected for analysis and stored in labeled Ziploc® bags until ready for sample analysis. Each sample was weighed individually and approximately 50 mg of each sample was wrapped in industrial-grade aluminum foil and prepared for fusion in a vacuum furnace. Fusion occurred at 900°C for 45 minutes to release all helium (Darrah and Poreda, 2012; Moore, 2016).

After fusion, the volume of gas was determined using a four digit MKS capacitance manometer (Darrah et al., 2014; 2015). Sample gas was then sequentially purified using a Zr-Al getter, a 707 SAES getter, and charcoal at liquid nitrogen temperatures (Jackson et al., 2013). The purified helium gas was inlet into a Thermo Fisher Helix SFT noble gas mass spectrometer for peak height comparison to a standard of 0.77 micro cubic centimeters (μcc) of dry atmospheric gas (Darrah and Poreda, 2012). The final values are reported in μcc/kg of ^{4}He and pcc/kg of ^{3}He.

2.2.2 Methodology for Calculations

Coalbed methane is already massively exploited in the Powder River Basin. In 2008, 535 bcf of CBM were produced. In 2009, estimations of CBM in the PRB totaled 37 trillion cubic feet (Luppens et al, 2015). CBM is stored in interbedded sandstone units that lie superior to coalbeds within the basin. This study investigates helium content in coalbed solids targeted to CBM extraction. These data presented herein, while collected from a small portion of total CBM in the PRB, are extrapolated to represent the entire Tongue River Member of the Fort Union Formation, while recognizing that this is a limitation of the current study. The remaining volumes of coal are reported in Table 2. Measured average values of helium are reported in Table 3.

Table 2. Coalbed Stratigraphy and Resources in the Powder River Basin. Image courtesy of USGS "Coal Geology and Assessment of Coal Resources and Reserves in the Powder River Basin, Wyoming and Montana," (Luppens et al., 2015).

Coal bed stratigraphy, original and available resources, and thickness						
Formation name	**Coal beds identified in this assessment**	**Original resources calculate (millions of tons)**	**Available resources calculated (millions of tons)**	**Maximum thickness (feet)**	**Average thickness (feet)**	
Wasatch	Upper Healy	6,863	5,327	17	12	
	Healy/Lower Ulm	13,004	10,738	83	14	
	Murray	2,664	599	14	3	
	Ucross	6,808	4,492	40	7	
	Upper Felix	2,122	1,205	19	4	
	Felix	18,759	16,784	55	12	
	Lower Felix	19,385	14,929	53	7	
Fort Union (Tongue River Member)	Roland Upper Rider	13,506	8,304	32	4	
	Roland Lower Rider	3,257	1,693	20	4	
	Roland (Baker, 1929)	47,774	43,336	40	10	
	Roland (Taff, 1909)	3,403	1,290	27	3	
	Upper Smith	1,036	430	36	3	Wyodak-Anderson coal zone
	Smith	126,433	122,868	278	24	
	Anderson Upper Rider	272	44	18	3	
	Anderson Lower Rider	755	480	20	8	
	Anderson	125,481	101,825	225	24	
	Lower Anderson	3,382	2,039	44	4	
	Dietz 1	1,138	495	29	4	
	Dietz 2	2,992	2,032	37	6	
	Dietz 3	50,880	45,063	119	13	
	Dietz 4	1,765	807	20	3	
	Upper Canyon/Cox	5,968	4,711	31	7	
	Canyon	147,450	135,454	183	21	
	Lower Canyon	59,528	52,056	85	11	
	Upper Ferry	814	464	10	4	
	Ferry	6,396	4,277	28	5	
	Werner/Cook	73,986	63,353	90	13	
	Upper Otter	919	604	21	4	
	Otter	71,021	64,310	170	14	
	Gates/Wall	66,426	57,851	125	9	
	Pawnee	24,498	16,964	34	7	
	Brewster-Arnold	1,968	475	19	5	
	Odell	11,676	6,581	26	4	
	Cache	3,303	809	26	3	
	A Zone	111	15	9	3	
	Upper Rosebud/S1	209	54	15	3	
	Rosebud/Knobloch	64,401	47,091	73	12	
	Calvert	1,162	196	18	3	
	McKay/Nance	33,289	22,614	36	5	
	Lower McKay/S2	190	1	7	3	
	Flowers-Goodale	60,544	51,064	40	8	
	Upper Witham	117	68	29	4	
	Robinson/Witham	20,677	15,007	41	7	
	Roberts/Terret	51,866	44,467	42	8	
	Burley	1,632	684	10	3	
	Upper Stag	1,870	790	13	3	
	Lower Stag	151	11	6	3	
	TOTAL TONS	1,161,851	974,751			

Table 3. CBM ^4He Content in Certain Coal Units in the Powder River Basin. Samples courtesy of Maverick Energy.

Coalbed	Measured ^4He (μcc/kg)
Knobloch-1 Outcrop	9451.1
Knobloch-2	19684.1
Knobloch-3	23068.0
Knobloch Average	**17401.07**
Goodale-1	16938.5
Goodale-2	9847.1
Goodale-3	13120.1
Goodale-4	11654.1
Goodale-5	31446.6
Flowers-1	18754.6
Flowers-2	9235.1
Flowers-Goodale Average	**15856.59**
Overall Average	**16319.93**
Lebo-1	19249.0
Median	16629.21

The values in Table 3 are broken out to the level of specific coal seams and then combined to estimate maximum resource potential. See tables 4, 5, and 6 in the following section for these calculated values. Note that "Lebo-1" is not included in Table 2, and therefore ^4He values measured in this unit are not included in final calculations for total volume in the Fort Union and Wasatch Formations. The following conversion factors are used to estimate values in the table.

short tons or tons (2,000 lbs) * 0.90718474 = metric tons (2,204.6 lbs)

1 lbs * 0.4536 = 1 kg

1 μcc/kg * 1,000,000 = 1 cc

1 cc * 1,000,000 = 1 m^3

1 m^3 = 35.31 ft

2.3 Results

Estimates for total helium content are based on average ^4He concentrations in coal seam solids for corresponding CBM units. Note that these results are widely assumed, as CBM ^4He concentrations from a small fraction of total coal is applied to the entire Fort Union and Wasatch Formations. Potential ^4He volumes for original coalbed solid resources in the PRB are approximately 17.2 million cubic meters, or 607.4 thousand mcf. Potential ^4He volumes for available coalbed solid resources are 14.4 million cubic meters, or 509.6 thousand mcf. In 2015, the price for private, Grade-A helium was ~200 USD per thousand cubic feet or mcf (Hamak, 2016). This puts the current value of available helium after refinement at nearly 102 million USD.

Coal resource data used to calculate available ^4He are from 2015, and represent the most up to date statistics from USGS (Table 2). ^4He values for Lebo-1 as shown in Table 3 are not factored into ^4He content in Tables 4 and 5 because coalbeds in the Lebo shale represent an insignificant portion of coal in the PRB. The term "ton" represents 2,000 standard US pounds. The abbreviation "μcc" represents micro cubic centimeters (see conversion data above). The following tables and figures show the results for volumetric ^4He calculations. Tables 4 and 5 show these calculations with intermediate steps. Figures 8 and 9 show a graphical representation of calculated ^4He volumes for original and available resources in the PRB, in both mcf and cubic meters.

Table 4. Potential ^{4}He Volume of Original Coalbed Solid Resources. Coalbed solid resource data Courtesy of USGS "Coal Geology and Assessment of Coal Resources and Reserves in the Powder River Basin, Wyoming and Montana," (Luppens et al., 2015). Samples courtesy of Maverick Energy.

Coalbed	Knobloch	Flowers-Goodale	Knobloch + Flowers-Goodale	Fort Union + Wasatch Formations
Original Resources (millions of tons)	64,401	60,544	124,945	1,161,851
Original Resources (kg)	5.84E+13	5.49E+13	1.13E+14	1.05E+15
Average Measured 4He Values (µcc/kg)	17,401.07	15,856.59	16,319.93	16,319.93
Calculated Volume of 4He in Original Resources (µcc)	1.02E+18	8.71E+17	1.85E+18	1.72E+19
Calculated Volume of 4He in Original Resources (m^3)	1,016,650.14	870,931.17	1,849,865.76	17,201,715.85
Calculated Volume of 4He in Original Resources (mcf)	35,897.92	30,752.58	65,318.76	607,392.59

Table 5. Potential ^{4}He Volume of Available Coalbed Solid Resources. Coalbed solid resource data Courtesy of USGS "Coal Geology and Assessment of Coal Resources and Reserves in the Powder River Basin, Wyoming and Montana," (Luppens et al., 2015). Samples courtesy of Maverick Energy.

Coalbed	Knobloch	Flowers-Goodale	Knobloch + Flowers-Goodale	Fort Union + Wasatch Formations
Available Resources (millions of tons)	47,091	51,046	98,137	974,751
Available Resources (kg)	4.27E+13	4.63E+13	8.90E+13	8.84E+14
Average Measured 4He Values (µcc/kg)	17,401.07	15,856.59	16,319.93	16,319.93
Calculated Volume of 4He in Available Resources (µcc)	7.43E+17	7.34E+17	1.45E+18	1.44E+19
Calculated Volume of 4He in Available Resources (m^3)	743,390.19	734,301.54	1,452,961.51	14,431,617.93
Calculated Volume of 4He in Available Resources (mcf)	26,249.11	25,928.19	51,304.07	509,580.43

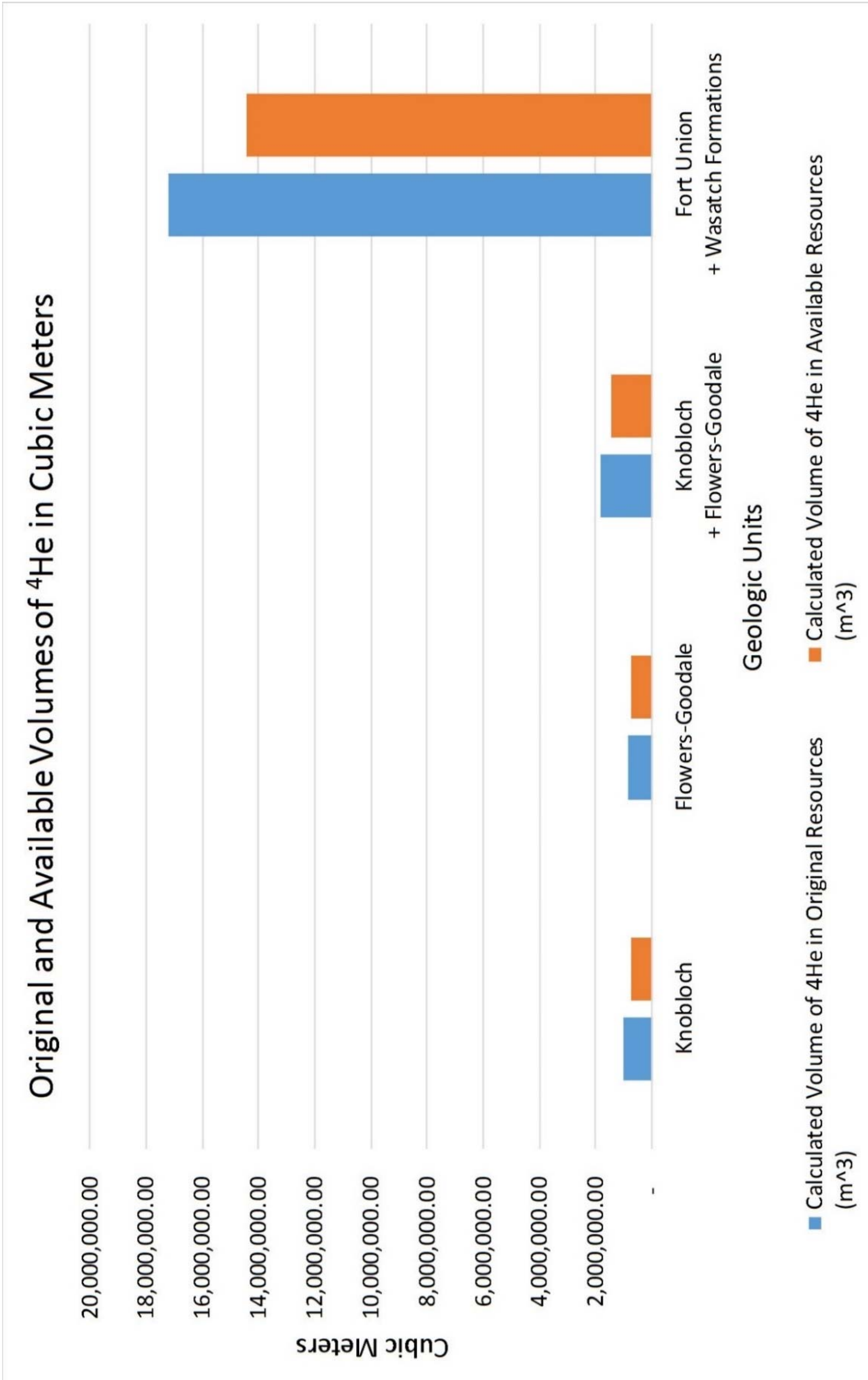

Figure 8. Original and Available Volumes of ^{4}He in Cubic Meters.

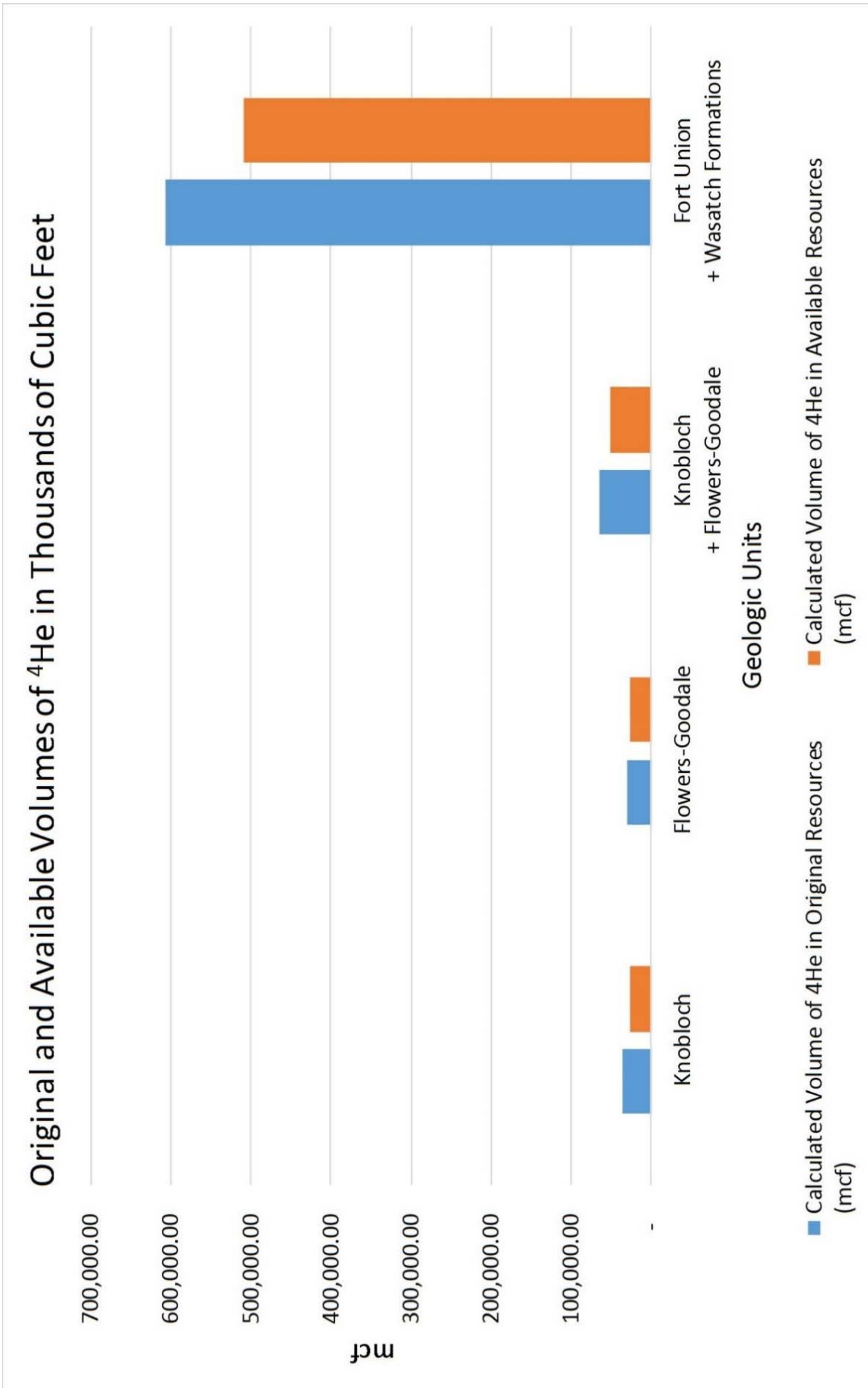

Figure 9. Original and Available Volumes of ^{4}He in Thousands of Cubic Feet.

2.4 Discussion

Helium production from coalbed solids in the Powder River Basin relies on the economic and practical viability of coal produced from the region. While original estimated coal resources from the Fort Union and Wasatch Formations alone constitute 1.16 trillion short tons (Luppens et al., 2015) (Table 2), the present study shows estimations of volumetric ^{4}He concentrations to equal only 509.6 thousand mcf, or 14.4 million cubic meters. This volume is insignificant when compared to current methods of production. In 2015, the U.S. alone consumed 43 million cubic meters, and produced 76 million cubic meters (Hamak, 2016). This means that if the entire coal content of the PRB were refined solely for helium extraction, the volume of helium produced could only meet U.S. demands for approximately three to four months if consumption remains consistent. Inconsistent concentrations would have almost no effect on the outcome of economic viability of this study. CBM measured elsewhere in the basin must contain drastically increased concentrations of ^{4}He before any impact could be made.

The PRB remains the nation's most active coal producing field, with less than 1% of estimated total coal resources being mined so far (Luppens et al., 2015). Current coal burning practices alone represent relatively high environmental risks and a negative impact in the public eye. The idea of using even the most helium-rich coal discovered thus far, solely as a source of helium is not economically, technically, or environmentally feasible. Nevertheless, coal still has the potential to represent a backstop, or even minor resource for helium refinement. With market and production volatility persisting for future years, no solution should be completely ruled out. However, clearly at the time of writing, natural gas from conventional wells still represents the best solution for helium production. I reach this conclusion because shale gas contains only trace amounts of helium and does not represent a viable source. As unconventional natural gas poises itself to replace conventionally produced natural gas, helium production, at least domestically, may be critically threatened.

The future of helium consumption must also be considered when looking at future helium sources. As shown in Figures 2 and 3, domestic consumption has steadily decreased since the year 2000, despite the increased demand for helium applications globally. Future efficiency of helium uses has the potential to greatly lessen the worlds helium dependency; however, unconventional natural gas market trends complicate this seemingly lone variable. The very idea of a backstop solution of helium may be a distraction from more practical and indirect solutions. The potential for renewable resources replacing fossil fuels may be far off, but improving technologies in industries, such as the automobile industry, lessen demand for crude oil. In the same way, helium recycling and new, more responsible applications could have a similar effect on demand. More problems arise from this though; if there is not a demand for new Grade-A helium, the rate of venting will increase, which could result in the same volume of helium loss.

Private exploitation companies should look toward refining and storing quantities of helium that are not feeding market demand and may be lost to the atmosphere. This practice would not only lead to a more competitive market, but also decrease the risk of sudden helium shortages. While this would not carry immediate economic success, creating the potential for privately, and competitively stockpiled helium for the future could be a worthwhile investment for interested parties.

2.5 Conclusions

This study summarized the history of helium production and consumption in the United States in order to put the future of the helium market into historical context. It also explored potential backstop resources of helium, specifically coalbed solids in the Powder River Basin, in Wyoming and Montana.

The history of helium production and demands in the United States has remained steady, yet volatile. Government stockpiling and subsequent laws requiring the sale of the federal helium reserve have led to discussions of an imminent helium shortage. The Helium Stewardship Act of 2013 has promised a smoother transition for the federal helium reserve's eventual privatization, although market volatility of conventional natural gas has put helium production at risk. Analysis of U.S. and global helium reserves place a potential helium shortage within the next 50 years, assuming steady production.

Given this information, the opportunity to study other helium resources has become relevant. Recent CBM analysis of coalbeds in the PRB have shown abnormally high concentrations of ^4He. Assuming constant concentration across all coalbeds,14.4 million cubic meters potentially exists in the basin's entire 1.15 trillion short tons of in place coal resources. This volume represents a value of nearly 102 million USD using 2015 helium prices. While this volume does not represent a practical solution to the helium problem, the potential for coal to become a backstop source of helium exists. At the time of writing, conventional natural gas remains the most promising source of helium for the future.

If nothing else, this study uncovers the alarmingly small amount of helium mankind has at its disposal and the extreme implications on market, economy, military, communication, and medical and technological advancement if the wasteful practice of this precious resource continues. The outlook for a single human lifespan appears grim, although new, more efficient technologies and future exploratory studies have the ability to undermine our dependency on helium, and point us toward renewable helium solutions.

2.6 Suggestions for Further Research

Future studies of coalbed methane at the Powder River Basin could make this study much more comprehensive. Using exact measurements for helium content in other coalbeds would yield much more reliable figures. Future studies at the PRB should focus on helium concentrations in existing CBM wells.

Any study that proposes the examination of helium content in future natural gas or oil plays could be beneficial. Current studies show shale gas and unconventional natural gas as unviable helium resources; however, studies on helium concentration in these gases should be performed in the future due to the increasing value of shale gas over conventional natural gas, and the potential need to source helium elsewhere. Studies that seek to improve industry recycling practices would be equally, if not more, beneficial than those that seek to find sources of helium beyond conventional natural gas. Studies in improving the efficiency of end uses of helium would be additionally beneficial to recycling.

Analysis of helium concentrations in CO_2 emissions from certain coal burning power plants, especially those that receive coal from the Powder River Basin and Illinois Basin, should also be done. It is unknown if exhaust, which is commonly scrubbed for sulfur oxides and may eventually be captured for CO_2 sequestration or enhanced oil recovery (EOR), could represent a passive source of economically viable helium collection.

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